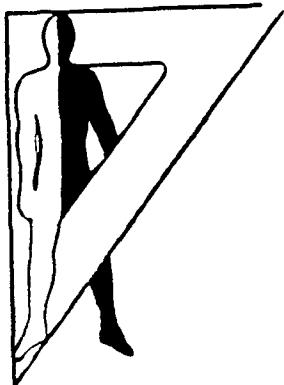


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Technical Note 9-92

ENHANCEMENT OF VIDEO IMAGERY BY MODIFIED INTENSITY-DEPENDENT SPATIAL SUMMATION

Phillip G. Harnden
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July 1992
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ENHANCEMENT OF VIDEO IMAGERY BY MODIFIED INTENSITY-DEPENDENT SPATIAL SUMMATION

INTRODUCTION

Cornsweet and Yellott (1985) proposed a model of retinal functioning which relates output to input by means of a variable width spread function. They theorized that an excitatory effect is induced on the receiving points of the retina from the luminance in a scene and that this excitation is not self-contained but is laterally spread to neighboring points. The resultant output neural image is resolved by a cumulative excitatory process stimulated by the intensity of the input retinal image. They supported their proposition by demonstrating that their model predicts certain well-known visual phenomena, such as Mach bands (edge enhancement), Ricco's Law (area summation effects in detection thresholds), and Weber's Law (threshold proportionality constancy).

The resultant level of excitation at any one point of the retina is determined by the summation of the amount of direct excitation and the contributory amounts from neighboring points. It is assumed that for each input retinal intensity there is an associated point-spread function that is nonlinear and strictly positive. For each input retinal image, an output image is produced that is the summation of the point-spread functions generated from each input point. The height of the point-spread function is directly proportional to the light intensity received, and the volume of the point spread is constant. The cumulative process is referred to as intensity-dependent spatial summation (IDS). The behavioral characteristics and assumptions just described are the nucleus of the restoration algorithm. In our exposition of the IDS model and its modification, a Gaussian point-spread function is used to model the excitatory behavior previously described and to demonstrate its ability to restore degraded digital images.

INTENSITY-DEPENDENT SPATIAL SUMMATION (IDS)

In terms of digital image processing, the luminance of a retinal image can be conceived as the gray level values of a two-dimensional matrix of pixels.

Let $I(x, y)$ denote the input image intensity or gray level at pixel (x, y) . $O[I(x, y)](p, q)$ then denotes the output gray level value of pixel (p, q) corresponding to the input image $I(x, y)$. The basic idea of the model is that each input pixel produces a nonnegative point spread which will cross onto neighboring pixels. The size of the spread generated will depend on the gray level of the input pixel. From this point spread, a contributory gray level value will be made to neighboring pixels, the amount of which will depend on the gray level of $I(x, y)$ and the distance of neighboring pixels (p, q) to the point (x, y) . The general form of the spread function S that gives the contribution of $I(x, y)$ to (p, q) is

$$S((x, y), (p, q), I).$$

S can be written as a function of two real variables by the following notation:

$$S([(x-p)^2 + (y-q)^2], I).$$

The output image is the summation of the point-spread functions or

$$O[I(x,y)](p,q) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x,y) \cdot S[I(x,y) \cdot [(x-p)^2 + (y-q)^2]] dx dy \quad (\text{Eq. 1})$$

in which

I = intensity or gray level,
 x = lateral input coordinate,
 y = vertical input coordinate,
 p = lateral output coordinate, and
 q = vertical output coordinate.

As with Cornsweet and Yellott, S is the Gaussian

$$S(x^2+y^2) = (1/2\pi) \cdot \exp[(-1/2) \cdot (x^2+y^2)]$$

The point spread around any input pixel (x,y) with gray level value $I(x,y)$ becomes

$$[I(x,y)/2\pi] \cdot \exp[(-1/2) \cdot I(x,y) \cdot [(x-p)^2 + (y-q)^2]].$$

In the Gaussian case, I in the domain of S behaves as the reciprocal of the variance. Hence, I inside of S controls the width of the spread, and I outside of S controls the height. The area under the spread remains constant, as the height and width of the spread change proportionally to the intensity. Unlike histogram equalization, which is sensitive only to the brightness domain, IDS has a spatial component.

It is assumed that S is nonnegative and that S is spatially homogeneous and circularly symmetric. Figure 1 shows a two-dimensional model of a Gaussian point-spread function.

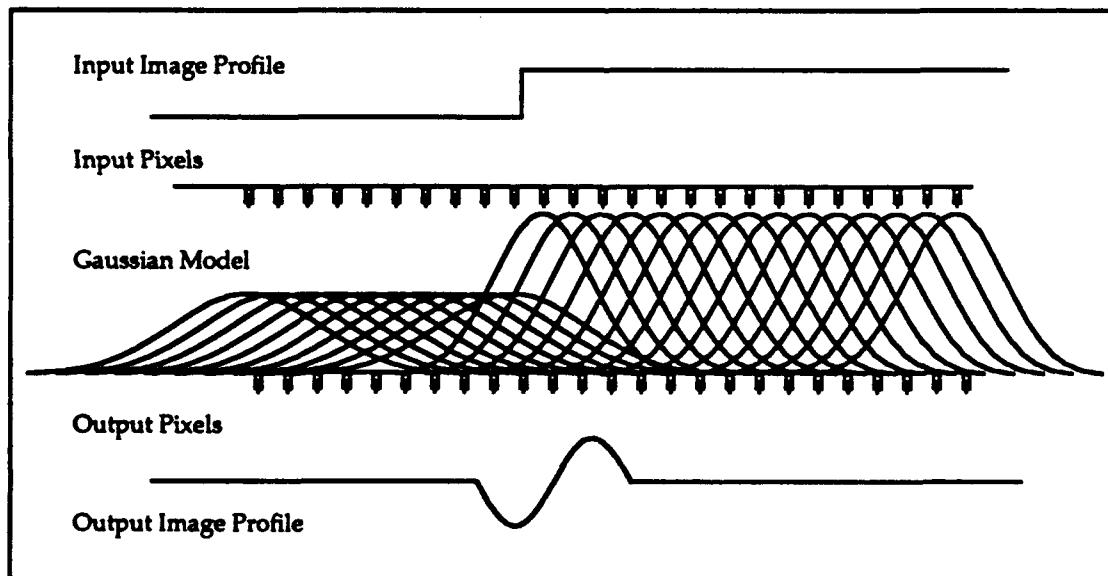


Figure 1. Schematic drawing of the IDS model (Cornsweet and Yellott, 1985).

The top of the Gaussian curves represents the initial gray level for each pixel in the input image. The points of intersection below each pixel correspond to the contribution of gray level from neighboring pixels. The initial gray level value and the values defined at the points of intersection are summed to produce a resultant output value for each pixel in the output image profile. As shown in Figure 1, the output image profile shows a gain in contrast at the location where a gray level difference occurs in the input image.

The Gaussian point-spread function will result in a three-dimensional circularly symmetric Gaussian volume, as shown in Figure 2. In this instance, the portion of volume area resting above an enclosed pixel will be used to determine the amount of gray level contribution.

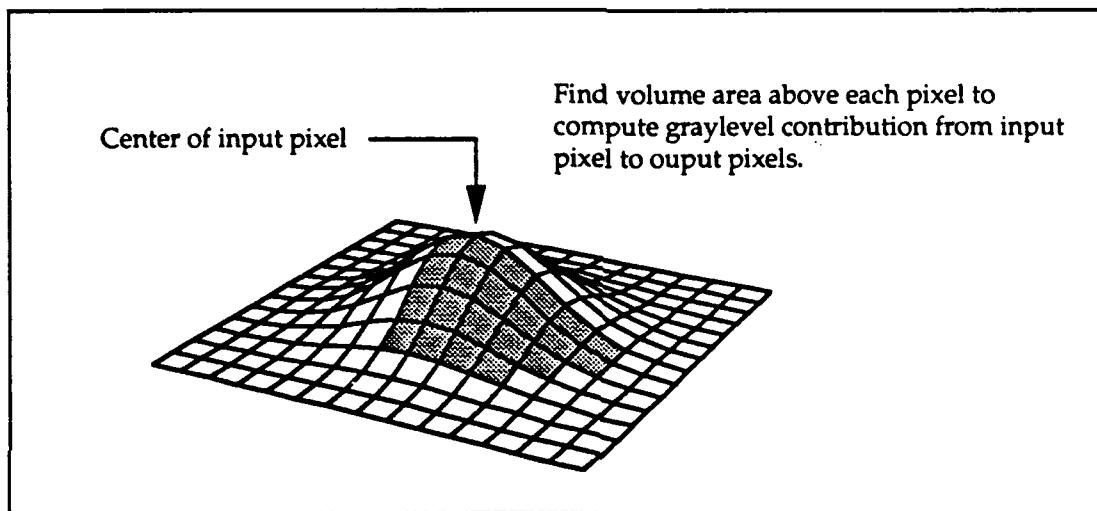


Figure 2. Three-Dimensional perspective of the Gaussian point-spread function.

All the digital images presented in this paper are quantized into 256 discrete levels of gray. Figure 3 shows an illustration of edge enhancement of a simple image using IDS.



Figure 3. Example of IDS processing (a) original image, (b) IDS result.

As shown in Figure 3(b), the edge of the interior box of the image is highlighted by the IDS model. Also note as the edge of the interior box is approached from the left (the low gray level side), there is a drop in the gray level values at the pixels just left of the edge. This result occurs because the gray levels of the pixels on the right of the edge are generating narrower spreads, and thus contributing less gray level to their neighboring pixels on the left side. Likewise, this behavior works in the opposite manner moving from high to low gray levels. The result is a slight dark and light band at the edge of the interior box. The width of the bands depends on the size of the spreads generated for the input gray levels, $I(x,y)$.

From Cornsweet and Yellott, the width of the Gaussian function is defined in the interval of ± 3 standard deviations, as related to retinal photoreceptor width. The effective width of the Gaussian point spread is given as $6/\sqrt{I} \cdot T$, where T equals the width of a photoreceptor. Using a like interpretation for a digital image, T becomes the width of an image pixel. As an example, if T equals the value $1/8$, the point spread would shrink to a single pixel at a gray level of 2304. Determining the appropriate T for the resolution and gray scale of the digital image is the critical parameter in the model's ability to enhance its visual features. Figure 4 shows an IDS processed digital image with T equal to $1/8$.



Figure 4. Example of IDS processing of a digital image of low contrast and low brightness (a) original image, (b) IDS processed image with $T=1/8$.

SPATIAL CONTRAST ENHANCEMENT (SCE)

It is apparent from Figure 4, that IDS processing, although producing edge enhancement, loses some important information. To enhance edges, IDS moves the gray levels of the output image toward a uniform value, except at those points where a sharp transition in gray level occur. This behavior produces a loss in brightness gradations (shape-from-shading cues) and gives the imagery a "flat" appearance, making perception of form and depth difficult. Furthermore, incidental to edge enhancement is the occurrence of blur. Because of the nature of the Gaussian model and the summation behavior of IDS, blurring will occur at the exact locations where enhancement occurs. The amount of blurring introduced is tied to the size of the point spreads generated. These negative side effects of IDS can be limited by restricting the width of the point-spread function, thereby decreasing blur while preserving brightness gradations.

From the formulation of the IDS model (Eq. 1),

$$O[I(x, y)](p, q) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x, y) \cdot S[I(x, y) \cdot \{(x-p)^2 + (y-q)^2\}] dx dy$$

we introduce three multiplicative parameters in the following manner

$$O[I(x, y)_{k-1}](x, y)_k =$$

$$A \cdot \left(\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (B_{k-1} \cdot I(x, y)_{k-1}) \cdot \right.$$

$$S\{(B_{k-1} \cdot I(x, y)_{k-1}) \cdot \{(x_{k-1} - x_k)^2 + (y_{k-1} - y_k)^2\}\} dx_{k-1} dy_{k-1} \quad (\text{Eq. 2})$$

in which

O = output image;

I = pixel gray level;

A = gray level multiplier, $A \geq 1$;

B = fractional gray level multiplier, $0 < B \leq 1$;

k = processing iteration number, initially, $k = 1$;

S = the Gaussian spread function;
whose effective width is determined by

$$6/\{\sqrt{B_{k-1} \cdot (I(x, y)_{k-1} \cdot (T \cdot C))}\}$$

where

T = the width of an image pixel;

C = multiplier to collapse the point-spread range, $C \geq 1$;

x_{k-1} = horizontal coordinate of the center of the input pixel;

y_{k-1} = vertical coordinate of the center of the input pixel;

x_k = horizontal coordinate of the center of the output pixel; and

y_k = vertical coordinate of the center of the output pixel.

The function of parameter C is to collapse the gray level range producing point spreads that impact neighboring pixels (i.e., establishing a gray scale window for IDS processing). Parameter B proportionally lowers the gray level of the entire input image into the allowable processing window set by C . Parameter A elevates the gray level of the resultant output image proportionally to the original gray scale.

Additionally, iteration is introduced to maximize the contrast enhancement produced during processing. In this case, after the input image data have been scaled to meet the processing criteria established by C and the data are processed, the resultant output image may contain pixel values that now exceed the IDS processing window defined by C . The resultant output data can be subsequently lowered after each processing pass to again fit the processing window. Multiple processing passes are achievable until the resultant image data can no longer be pushed into the IDS processing window by parameter B without losing image data at the lower boundary of the processing

window (i.e., gray level 0). At this point, the contrast of the image has been maximized by the point-spread function. Parameter A is now used to elevate the gray level of the output proportionally to the original gray scale.

In the digital processing implementation of the IDS model, point spreads of at least two pixels in width are required, one pixel each side the center of the Gaussian, to yield neighboring gray level contributions. As an example, with $T=1/16$ and $C=6$, the model will establish an IDS processing window (point spreads of at least two pixels in width) between the gray levels of 1 and 64. (The same result is achieved if $T=6/16$ and C is ignored, but we choose to use C for expository reasons.) Gray level values above 64 will not produce a spread great enough to induce gray level contributions to neighboring pixels. Within this gray level range, the width of point spreads generated will be between 2 and 16 pixels. Figure 5 illustrates the effect of these additions on the IDS process.



Figure 5. Effects of modified IDS process (a) original image,
(b) modified IDS with $A=4$, $B_1=.73$,
 $B_2=.46$, $C=8$, and $T=1/16$.

From Figure 5, it is evident that the brightness-equalizing mechanism of IDS is overcome as brightness information is preserved. Also, by constraining the size of the point spreads generated, the introduction of blur is kept to a minimum. Because of the effectiveness of the modified IDS model to maintain and enhance shape-from-shading cues, the technique has been named spatial contrast enhancement (SCE).

RESULTS

Figure 6 depicts an input image, the application of SCE, and for the sake of comparison, the application of histogram equalization and the application of parameter A alone. As Figure 6 shows, brightening the image alone produces better resolution, but the SCE technique highlights the features of the face (e.g., the eyebrows, the cheek) by enhancing shape-from-shading cues. On the other hand, histogram equalization gives a flat, formless appearance because of the loss of quantization levels.

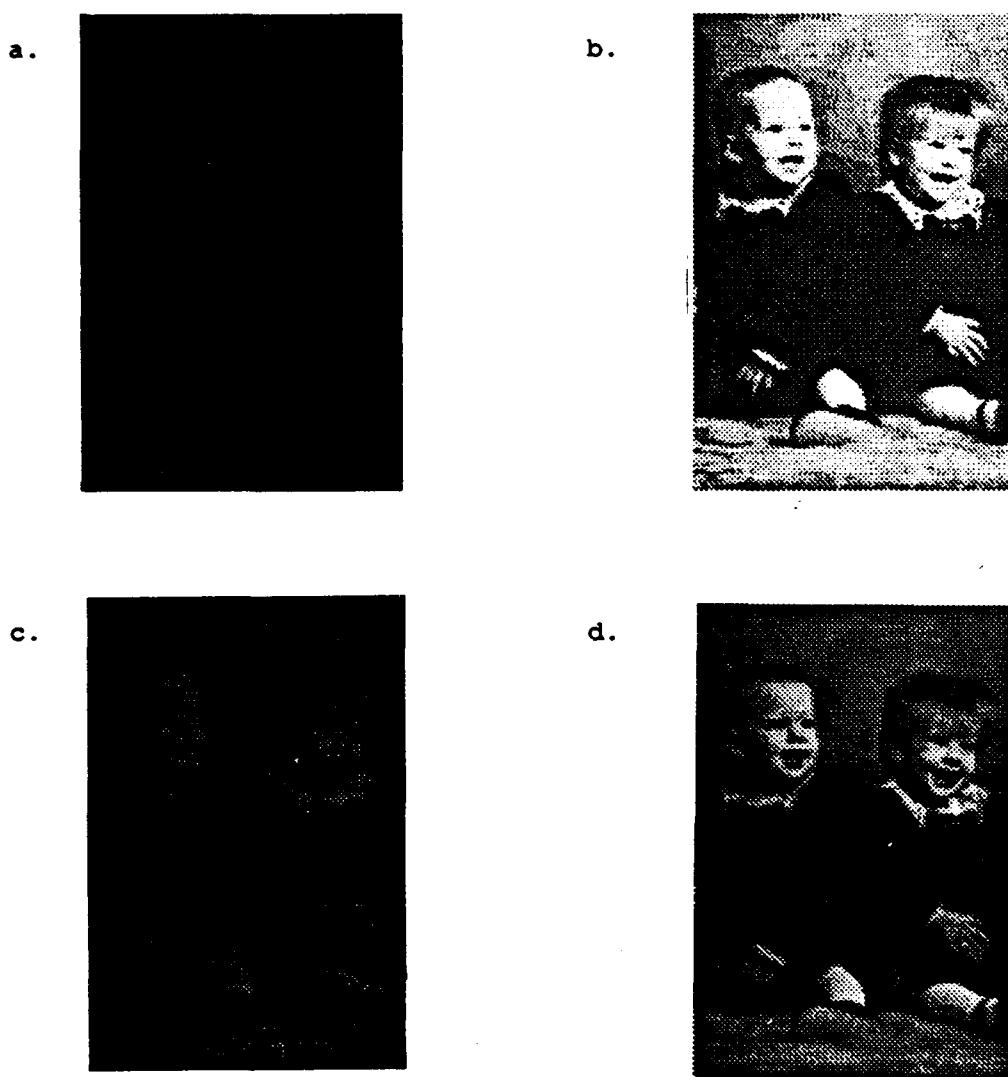


Figure 6. Kaitlin and Emily (a) original image, (b) histogram equalization, (c) brightening with $A=3$, and (d) SCE processed image with $A=3$, $B_1=1$, $B_2=1$, $C=8$, and $T=1/16$.

Figure 7 depicts the same processing techniques after the addition of high-frequency Gaussian noise at an S/N ratio of 3 to the input image. The noise is much more apparent in the image processed with histogram equalization than the one processed by SCE.

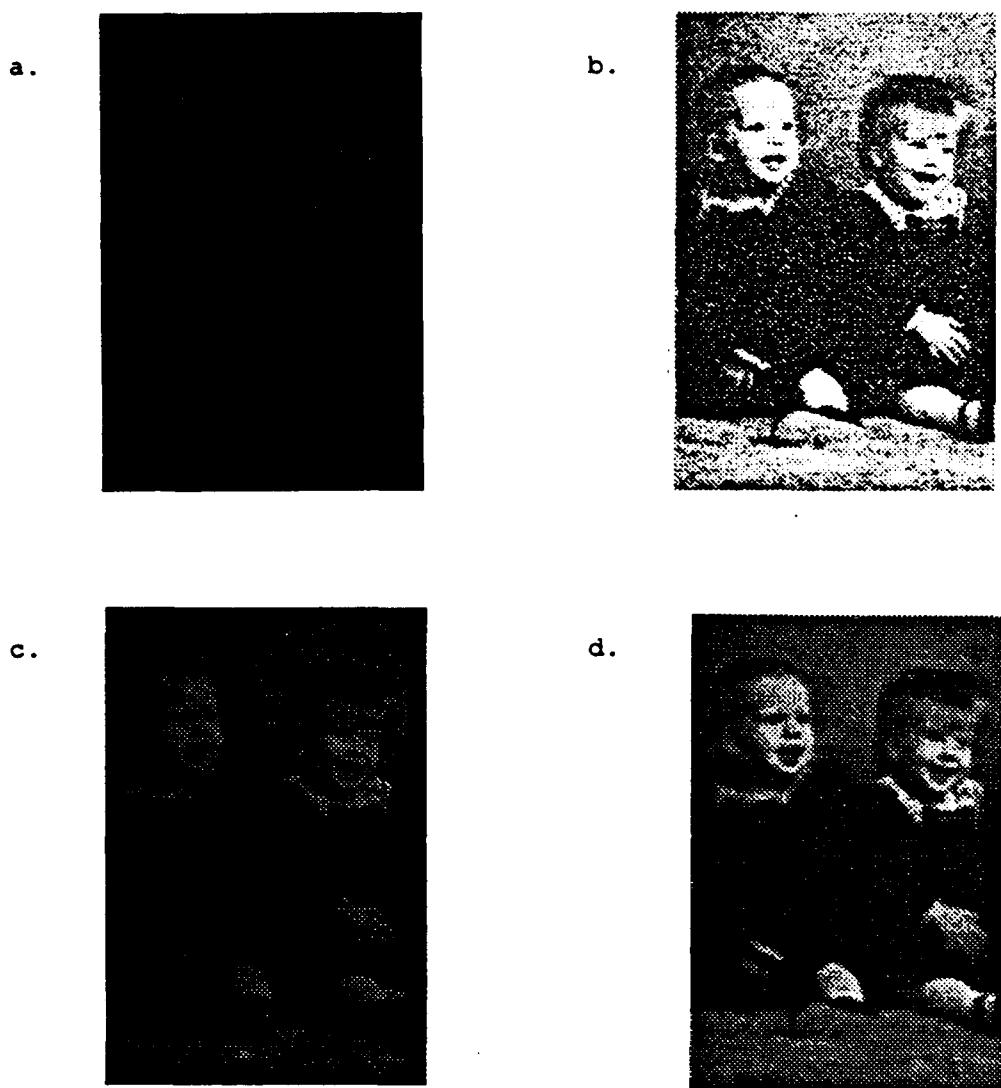
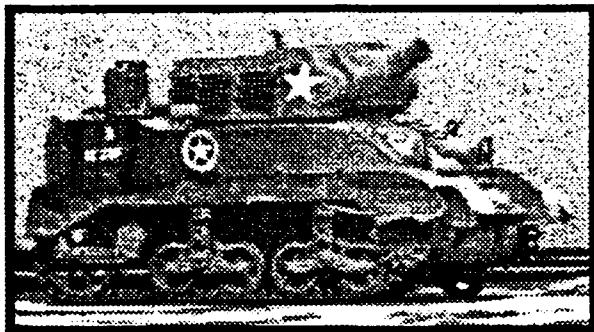


Figure 7. Processed images of Kaitlin and Emily containing high-frequency Gaussian noise (a) original image plus noise, (b) histogram equalization, (c) brightening with $A=3$, and (d) SCE processed image with $A=3$, $B_1=1$, $B_2=1$, $C=6$, and $T=1/16$.

And lastly, Figure 8 exhibits resultant images processed by histogram equalization and SCE. From Figure 8, it is not readily apparent which processing technique derives a more agreeable visual result. Histogram equalization does seem to be sufficient when shape-from-shading cues are not consequential to the visual understanding of the image (i.e., three-dimensional form is nonessential to perceptual understanding).

a.



b.

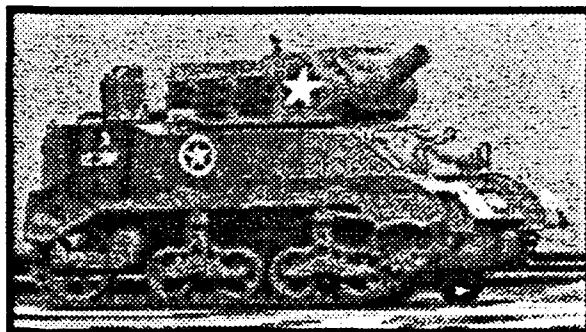


Figure 8. Example of image enhancement (a) image enhanced by histogram equalization, (b) SCE processed image with $A=2$, $B_1=1$, $B_2=.67$, $B_3=.35$, $C=6$, and $T=1/16$.

CONCLUSIONS

SCE, a modified form of IDS, is generally preferred to IDS as a contrast-enhancement algorithm because of its ability to preserve brightness gradations and minimize blur. However, IDS is more convenient to apply. SCE currently depends on subjective interpretations for assigning appropriate values to the multiplicative parameters A and C , the choice of which greatly affects the enhancement capability of the SCE process.

Although SCE produces some blur when compared to histogram equalization or brightening alone, in some applications, this effect is more than offset by the enhanced perception of form and depth which it precipitates.

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